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Hazard Analysis of Long Term Viewing of Visible Laser Light Off of Fluorescent Diffuse Reflective Surfaces (Post-It)

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Hazard Analysis of Long Term Viewing of Visible Laser Light Off of Fluorescent Diffuse Reflective Surfaces (Post-It)

By

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Abstract

A laser hazard analysis is performed to evaluate if the use of fluorescent diffuse reflectors to view incident laser beams (Coherent Verdi 10W) present a hazard based on the ANSI Standard Z136.1-2000, American National Standard for the Safe Use of Lasers. The use of fluorescent diffuse reflectors in the alignment process **does not pose an increased hazard** because of the fluorescence at a different wavelength than that of the incident laser.

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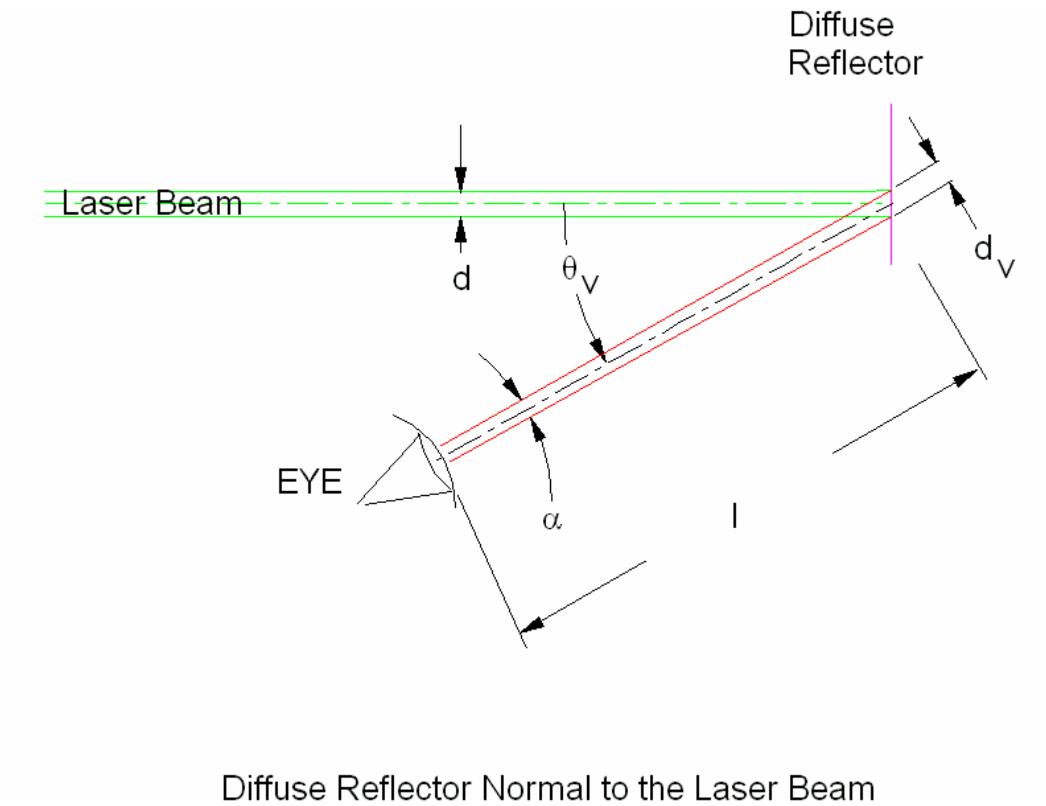


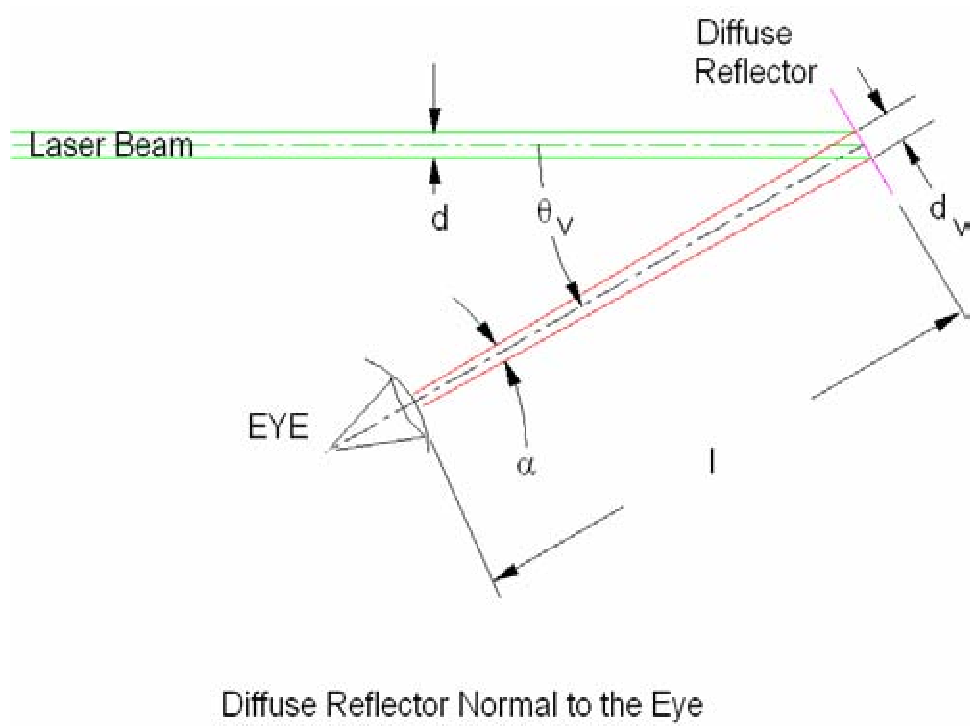
Figure 1

Viewing a diffused reflector oriented normal to the incident laser beam.

Diffuse reflectance surfaces are routinely used to indirectly view visible laser beams during alignment procedures. Fluorescence materials, such as "hot pink" Post-It® or like materials, are sometimes used with 'green" light emitting lasers. It is sometimes difficult to view indirect or diffused laser light while wearing typical laser safety eyewear specific for the laser wavelength. This is because the Optical Density of commercial eyewear is generally somewhat higher than the minimum Optical Density (ODmin) specific the individual laser in use. Additionally, the ODmin is calculated based on a quarter second exposure (Class 2 laser hazard level) and specific to intrabeam viewing of the laser beam and not from indirect or diffused viewing of the laser source. From a laser safety perspective it is necessary that the laser worker be protected against the possibility of an intrabeam exposure from the primary laser beam. Should that intrabeam exposure occur, the use of laser safety eyewear shall prevent the worker's exposure from being above the ocular Maximum Permissible Exposure (*MPE*). The laser worker is required to use laser safety eyewear with an optical density (*OD*) equal to or greater than the calculated ODmin for the laser in use.

The radiant output of the laser is typically reduced during laser alignments. In cases where the laser output stability is adversely affected by reducing the excitation source a attenuation or neutral density filter is inserted in the laser beam, generally at the exit of the laser. At this reduce radiance the beam may not be observable while wearing laser safety eyewear rated for the full power of the laser.

Alignment laser safety eyewear, with a reduced OD, is sometimes employed to allow the laser worker to see the laser spot and still offer a level of safety for the reduced laser output radiance. However; having two sets of laser safety eyewear (alignment and full protection) could lead to a situation where the "alignment" eyewear is inadvertently donned instead of the eyewear for full protection when the laser worker has the potential to be exposed to the intrabeam laser hazard at full power.



<u>Figure 2</u>

Viewing a diffused reflector oriented normal to the viewing axis of the eye

An alternate method (preferred method from a laser safety point of view), applicable for lasers with radiant outputs in the green part of the visible-spectrum is to use “hot pink” POST-ITS to indirectly view the laser beam spot while wearing full protective eyewear for the green because the material will re-emit or fluoresce in the red.

Example:

Laser:	
Manufacturer:	Coherent
Model:	Verdi-10w
Output:	
Radiance:	10 Watts
Wavelength:	532 nm
Diameter:	2.25 mm
Divergence:	0.5 mrad
Viewing Angle:	20 degrees
Viewing distance:	25 cm

II. <u>Intrabeam Hazard (Small Source)</u>

Class 2 Laser Hazard Analysis

For protection against the intrabeam exposure of the visible laser beam the standard duration is given in *ANSI Std. Z136.1-2000 (Table 4a)* as **0.25 seconds**.

The small-source ocular exposure MPE for visible lasers is given in the *ANSI Std.Z136.1-2000 (Table 5a)* as:

$$MPE = \frac{1.8 \times t^{0.75} \times 10^{-3}\ J/cm^2}{t} \qquad 400\ nm \le \lambda \le 700\ nm$$

$$18 \times 10^{-6}\ \sec \le t \le 10\ \sec$$

$$= 1.8 \cdot (0.25)^{-0.25} \times 10^{-3}\ W/cm^2$$

$$MPE = 2.55 \times 10^{-3}\ W/cm^2$$

Determination of minimum Optical Density

The minimum Optical Density required of the laser safety eyewear for inadvertent (reflex response – Class 2) intrabeam exposure protection can be calculated as follows:

$$OD_{\min} = \log_{10}\left[\frac{E}{MPE}\right] \qquad \text{[}\textit{ANSI Std. Z136.1-2000 (Eq. B98)}\text{]}$$

$$OD_{\min} = \log_{10}\left[\frac{\Phi / A_{\lim}}{MPE}\right] = \log_{10}\left[\frac{\dfrac{\Phi}{\pi \cdot (d_{\lim})^2 / 4}}{MPE}\right] = \log_{10}\left[\frac{4 \cdot \Phi}{\pi \cdot (d_{\lim})^2 \cdot MPE}\right]$$

$$OD_{\min} = \log_{10}\left[\frac{4 \cdot (10\ W)}{\pi \cdot (0.7 cm)^2 \cdot \left(2.55 \times 10^{-3}\ W/cm^2\right)}\right]$$

$$OD_{\min} = 4.01 \ @ \ 532\ nm$$

Beam Irradiance.

The maximum average irradiance (E) of this laser output beam is the ratio of the output radiance at full power (10 *Watts*) to the area of the laser beam (A_{beam}).

$$\overline{E}_{\max} = \frac{\Phi_o}{A_{beam}}$$

$$= \frac{\Phi_o}{\left(\frac{\pi}{4}\right) \cdot (d_o)^2}$$

$$= \frac{10\ W}{\left(\frac{\pi}{4}\right) \cdot (0.225\ cm)^2}$$

$$E = 252\ {}^{W}\!/_{cm^2}$$

Reduced Irradiance (Alignment)

The ANSI standard states that a potential fire hazard exists when laser beam irradiance is in excess of 10 Watts/cm^2 [*ANSI Std.Z136.1-2000 (7.5)*]. The laser output radiance would of necessity be reduced such that the beam would not burn through the diffuse reflective surface (fluorescent Post-It) during the alignment process. The maximum output radiance would be just below the irradiance level (E_{fire}) necessary to burn through the paper.

$$\Phi_{\max-align} = E_{fire} \cdot A_{beam}$$

$$= \left(10\ {}^{W}\!/_{cm^2}\right) \cdot \frac{\pi}{4} \cdot (0.225\ cm)^2$$

$$= \left(10\ {}^{W}\!/_{cm^2}\right) \cdot \left(0.0398\ cm^2\right)$$

$$\Phi_{\max-align} = 0.398\ W$$

The laser output radiance would have to be reduced to below 400 mw in order to be below the irradiance, for this beam diameter, necessary to prevent burning through the diffuse surface (Post-It) used in the alignment process.

III. **Long Term (Alignment) Diffuse Viewing**

Exposure Duration:

Typically the exposure duration of a visible laser during alignment procedures, where there is deliberate long term viewing of the light source is given by the ANSI Standard as **600 seconds** [*ANSI Std. Z136.1-2000 (Table 4a)*].

Small Source Analysis

The small source MPE is given in Table 5a of the *ANSI Std.Z136.1-2000* as:

$$MPE = 1\times10^{-3}\ {}^{W}\!/\!_{cm^2} \qquad [400\ nm \le \lambda \le 700\ nm]$$
$$[10\ \sec \le t \le 3\times10^{4} \sec]$$

The minimum Optical Density required of the laser safety eyewear for intended (Class 1) intrabeam exposure protection can be calculated as follows:

$$OD_{\min} = \log_{10}\left[\frac{E}{MPE}\right] \qquad [\textit{ANSI Std. Z136.1-2000 (Eq. B98)}]$$

$$OD_{\min} = \log_{10}\left[\frac{\Phi/A_{\lim}}{MPE}\right] = \log_{10}\left[\frac{\dfrac{\Phi}{\pi\cdot(d_{\lim})^2/4}}{MPE}\right] = \log_{10}\left[\frac{4\cdot\Phi}{\pi\cdot(d_{\lim})^2\cdot MPE}\right]$$

Full Power $(\Phi_o = 10\ Watts)$:

$$OD_{\min} = \log_{10}\left[\frac{4\cdot(10\ W)}{\pi\cdot(0.7cm)^2\cdot\left(1\times10^{-3}\ W/cm^2\right)}\right]$$

$$OD_{\min} = 4.41\ @\ 532\ nm$$

Reduced Power $(\Phi_o = 0.398\ Watts)$:

$$OD_{\min} = \log_{10}\left[\frac{4\cdot(0.398\ W)}{\pi\cdot(0.7cm)^2\cdot\left(1\times10^{-3}\ W/cm^2\right)}\right]$$

$$OD_{\min} = 3.01\ @\ 532\ nm$$

Extended Source Analysis

The viewing angle subtended by the eye of the circular laser spot on the non-specular reflective surface is given by:

$$\alpha = \frac{d_v}{l} \quad \text{, for } \alpha < 5^\circ$$

Where,

α: The angle subtended by the eye of the illuminating source

d_v: Is the beam diameter of a circular laser beam

l: The distance from the eye to the illuminating source

Extended source correction applies when the angle (α) subtended by the eye is greater than 1.5 milli-radians.

$\alpha_{\min} = 1.5 \ mrad$ [Notes to *ANSI Std.Z136.1-2000 (Table6)*]

In this case, where the beam divergence is very small (0.5 mrad) the laser beam cross-section remains approximately 2.25 mm in diameter for short distances from the laser.

Typical for hand held material in the beam path; the viewing distance (l), from the diffused reflective surface to the observer's eye, is given as 25 cm (approximately 10 inches). The viewing angle (θ_v), described by a line from the centerline of the laser beam path to the center of the laser spot on the diffuse reflective surface to the center line of the eye, is given as 20 degrees from the diffused reflective surface and the eye.

The angle (α) subtended by the eye to the laser spot on the diffused reflective surface is dependent upon the relative orientation of the diffused reflective surface: figure 1 depicts the reflective surface normal to the incident laser beam and figure 2 depicts the reflective surface oriented normal to the eye.

This viewing angle, (α), is the ratio of the smallest spot dimension to the distance from the spot to the eye. In figure 1, the smallest viewing spot dimension, for a circular spot, is the product of the beam diameter and the cosine of the off axis viewing angle, (θ_v). In figure 2, the smallest viewing spot dimension is the beam diameter. The actual observed smallest spot, on a hand held, diffuse reflector lies somewhere between these to two values. The worst case would use the smallest of all, the possible smallest spot dimensions (the example given in figure 1).

With reference to figure 1, the illuminated spot on the diffused reflective surface at this viewing angle (θ_v), will appear to the observer as elliptical in shape, with the major axis equal to the laser beam diameter at the point along the beam path that the diffuse reflective surface is inserted and the minor axis is equaled to product of the laser beam diameter at that point and the cosine of the viewing angle (θ_v) off the centerline of the beam path.

$$d_v = d \cdot \cos(\theta_v)$$

$$\alpha = \frac{d \cdot \cos(\theta_v)}{l}$$

$$\alpha = \frac{(2.25\ mm) \cdot \cos(20^\circ)}{250\ mm} = (9 \times 10^{-3}\ rad) \cdot (0.940)$$

$$= (9 \times 10^{-3}\ rad) \cdot (0.940)$$

$$\alpha = 8.46\ mrad$$

The viewing angle subtended is greater than the minimum angle so extended source correction can apply.

The appropriate MPE for extended-source ocular exposure to a laser spot for longer durations than the Class 2 reflex response is given the *ANSI Std. Z136.1-2000 (Table 5b)*.

The radiant wavelength of the laser (532 nm) is in the Dual Limit region and both the Photochemical as well as the thermal MPE limits must be evaluated. The appropriate extended-source MPE is the smaller of these to limit values.

$$MPE_{ES} = \min\ [MPE_{photochemical},\ MPE_{thermal}]$$

Photochemical MPE limit

The evaluation of the Photochemical MPE limit requires the determination of several factors.

Determining the limiting field of view (γ) for MPEs based on the photochemical hazard. The MPE photochemical limit is averaged over the cone angle (γ) which is dependent on the exposure duration (*t*), [*ANSI Std.Z136.1-2000 (Appendix B7.2)*].

The cone angle of the limiting field of view for a 600 second (standard) exposure is given by the ANSI Standard as:

[*ANSI Std. Z36.1-2000 (Eq. B87)*]

$$\gamma = 1.1 \times t^{0.5} mrad \qquad 100 \text{ sec} < t \leq 10{,}000 \text{ sec}$$

$$\gamma = 1.1 \times (600)^{0.5} mrad$$

$$\gamma = 26.94 \ mrad$$

The photochemical MPE is given in *ANSI Std. Z136.1-2000 (Table 5a)* for: $\alpha \leq 11 \ mrad$ and $\alpha > 11 \ mrad$, is based on integrated irradiance per steradian (solid angle).

The solid angle (Ω) can be determined by:

$$\Omega = \frac{\pi \cdot \alpha^2}{4} sr$$

If however; the angle (α) subtended is smaller than the limiting field of view angle (γ) then the limiting field angle is used instead [*ANSI Std. Z136.1-2000 (Note to Eq. B93)*].

Since $\alpha < \gamma$, then use γ in place of α:

$$\Omega = \frac{\pi \cdot \gamma^2}{4} sr$$

$$= \frac{\pi \cdot \left(26.94 \times 10^{-3} rad\right)^2}{4}$$

$$\Omega = 570 \times 10^{-6} sr$$

The appropriate photochemical MPE limit is:

ANSI Std. Z136.1-2000 (Table 5b)

$$MPE_{photochemical} = 100 \cdot C_B \ {}^{J}\!/_{cm^2 \cdot sr} \qquad 400 \ nm \leq \lambda \leq 600 \ nm$$

$$\gamma < 11 \ mrad$$

The wavelength correction factor in the photochemical hazard region is given by *ANSI Std. Z136.1-2000 (Table 6)* as:

$$C_B = 10^{20(\lambda - 0.450)} \qquad 450 \; nm \le \lambda \le 600 \; nm$$
$$= 10^{20(0.532-0.450)}$$

$$C_B = 43.65$$

$$MPE_{photochemical} = \left(100 \cdot C_B \; {}^{J}\!/_{cm^2 \cdot sr}\right) \cdot \Omega$$
$$= \left(100 \times 43.65 \; {}^{J}\!/_{cm^2 \cdot sr}\right) \cdot 570 \times 10^{-6} \, sr$$
$$MPE_{photochemical} = 2.49 \; {}^{J}\!/_{cm^2}$$

In terms of irradiance:

$$MPE_{photochemical} = \frac{2.49 \; {}^{J}\!/_{cm^2}}{600 \;\; \sec}$$

$$MPE_{photochemical} = 4.15 \times 10^{-3} \, {}^{W}\!/_{cm^2}$$

Thermal MPE Limit

The thermal extended source MPE limit is present in *ANSI Std. Z136.1-2000 (Table 5b – thermal limits)* as:

$$MPE_{thermal} = 1.8 \cdot C_E \cdot T_2^{-0.25} \times 10^{-3} \, {}^{W}\!/_{cm^2} \qquad 400 \; nm \le \lambda \le 700 \; nm$$
$$T_2 < t \le 3 \times 10^4 \sec$$

The extended source correction factor (C_E) is presented in *ANSI Std.Z136.1-2000 (Table 6)* as:

$$C_E = \frac{\alpha}{\alpha_{\min}} \qquad \alpha_{\min} \le \alpha \le \alpha_{\max}$$

$$= \frac{8.46 \ mrad}{1.5 \ mrad}$$

$$C_E = 5.64$$

The exposure duration (T_2) beyond which the thermal MPE for an extended source is constant in terms of irradiance and is given in *ANSI Std. Z136.1-2000 (Table 6)* as:

$$T_2 = 10 \times 10^{\left(\frac{\alpha - 1.5}{98.5}\right)} \qquad 400 \ nm \le \lambda < 1400 \ nm$$

$$= 10 \times 10^{\left(\frac{8.46 - 1.5}{98.5}\right)}$$

$$T_2 = 11.77 \ \sec$$

Since the standard exposure is expected to be 600 sec, the T_2 factor applies. The thermal limit extended source MPE is:

$$MPE_{thermal} = 1.8 \cdot C_E \cdot T_2^{-0.25} \times 10^{-3} \ {}^{W}\!/_{cm^2}$$

$$= 1.8 \cdot (5.64) \cdot (11.77)^{-0.25} \times 10^{-3} \ {}^{W}\!/_{cm^2}$$

$$MPE_{thermal} = 5.48 \times 10^{-3} \ {}^{W}\!/_{cm^2}$$

The appropriate MPE is the smallest of the photochemical and thermal limits [*ANSI Std.Z136.1 (Table 5b)*].

<u>Table 1</u>

Appropriate Extended-Source MPE for Long Exposure Durations

Limit	MPE $\left({}^{W}\!/_{cm^2}\right)$	Comment
photochemical	4.15×10^{-3}	smallest
thermal	5.48×10^{-3}	

Diffused Reflection

<u>Extended-Source Diffused Reflection</u>

The Nominal Ocular Hazard Distance (r_{NOHD}) from an extended source Diffused Reflection is given as:

$$r_{NOHD} = \sqrt{\frac{\rho_\lambda \cdot \Phi \cdot \cos\theta_v}{\pi \cdot MPE_E}} \qquad \textit{ANSI Std. Z136.1-2000 (Eq. B77)}$$

Where

r_{NOHD}:	Nominal Ocular Hazard Distance (in cm) from diffused reflection.
ρ_λ:	Diffused reflection factor at a wavelength, λ, $\rho_\lambda \leq 1$.
Φ:	Radiant Power, watts
θ_v:	Viewing angle from the normal of the reflecting surface
MPE_E:	Appropriate Maximum Permissible Exposure (Extended Source Corrected)

The diffuse reflection factor (ρ_λ) is set to the maximum (1.0) for a conservative safety bias.

$$r_{NOHD} = \sqrt{\frac{(1.0)\cdot(0.398\ W)\cdot\cos(20^\circ)}{\pi \cdot \left(4.15\times10^{-3}\ W/cm^2\right)}}$$

$$r_{NOHD} = 5.36\ cm$$

Viewing the diffuse alignment surface at 25 cm is outside the Nominal Ocular Hazard Distance.

<u>Small-Source Diffused Reflection</u>

Declining to apply extended source correction will yield a more conservative small source analysis with a strong laser safety bias.

The Nominal Ocular Hazard Distance (r_{NOHD}) from a small source Diffused Reflection is given as:

$$r_{NOHD} = \sqrt{\frac{\rho_\lambda \cdot \Phi \cdot \cos\theta_v}{\pi \cdot MPE}}$$ *ANSI Std. Z136.1-2000 (Eq. B77)*

Where

r_{NOHD}:	Nominal Ocular Hazard Distance (in cm) from diffused reflection.
ρ_λ:	Diffused reflection factor at a wavelength, λ, $\rho_\lambda \leq 1$.
Φ:	Radiant Power, watts
θ_v:	Viewing angle from the normal of the reflecting surface
MPE:	Appropriate Maximum Permissible Exposure (Small-Source)

Assuming worst case diffuse reflection of 100%:

$$r_{NOHD} = \sqrt{\frac{(1.0)\cdot(0.398\ W)\ \cdot \cos 20^\circ}{\pi \cdot \left(1 \times 10^{-3}\ W/_{cm^2}\right)}}$$

$$r_{NOHD} = 10.9\ \ cm$$

IV. Conclusion

The use of fluorescent diffuse reflectors in the alignment process does not pose an increased hazard because of the fluorescence at a different wavelength than the incident laser. The observing distance of 25 cm is outside both the extended-source and the more conservative small-source diffused reflection Nominal Ocular Hazard Zone and would be eye safe even without the use of laser safety eyewear. The fluorescent paper shifts the viewing wavelength into the red part of the spectrum outside the absorption band of the laser safety eyewear so it can be safely observed while wearing the laser safety eyewear for full protection against the primary laser beam, which is in the green part of the spectrum.

V. Acknowledgement

The author would like to acknowledge and thank Jonathan Snell (10327) and Alice Sobczak (5719) taking the time to perform a technical review of the report. Their inputs and comments were very much appreciated.

VI. Reference

ANSI Standard Z136.1-2000, for Safe Use of Lasers, Published by the Laser Institute of America.

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